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# UV radiation below an Arctic vortex with severe ozone depletion

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**Abstract.** The erythemally weighted (UV) irradiance below the severely depleted Arctic vortices in spring 1996 and 1997 were substantially elevated. On average the UV increased 36 and 33% relative to the 1979–1981 mean assuming clear skies from day 80–100 in 1996 and 1997, respectively. On clear sky days large regions of the Arctic experienced maximum UV increases exceeding 70 and 50% on single days in 1996 and 1997, respectively. A minor fraction of these increases are not anthropogenic and have a dynamical origin as seen by comparison to 1982, when hardly any ozone depletion is expected.

## 1 Introduction

Concentrations of ozone depleting substances are decreasing slowly, so we can expect several years with current levels of ozone depletion (WMO, 2003; Knudsen et al., 2004). But exactly how bad is the current situation? One place where substantially elevated levels of UV radiation are expected is below a severely depleted vortex during springtime. This can happen in Antarctica and southern parts of South America (Pazmiño et al., 2004) and in the Northern Hemisphere (NH) high latitudes. The NH is the focus of this paper. During passage of an ozone mini-hole and a severely depleted vortex on March 6, 1996, Seckmeyer et al. (1997) found a substantial increase in UV even at 47° N. Latitude dependent UV trends from satellite data have been estimated by Herman et al. (1996) for the period 1979–1992. During April the largest NH trends occur north of 50° N (WMO, 1999).

Taalas et al. (2000) calculated the UV increase expected in the future from general circulation model predictions, and found April mean UV increases in the period 2010–2020 exceeding 90% of the 1979–1992 average for the worst case

scenario. We document here what levels of UV we have already experienced and are likely to experience in the foreseeable future.

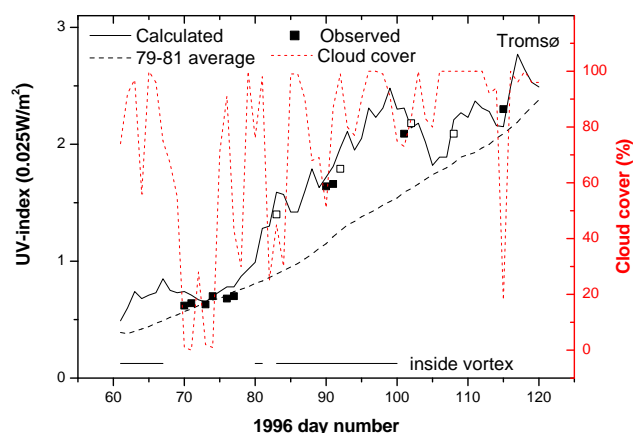
The importance of UV radiation levels in spring in the Arctic can be seen from Jokela et al. (1993), who found that on a vertical surface noon-time UV irradiances were higher at the end of April than at any other time of the year in northern Finland. The amount of UV reaching a vertical surface has important biological implications, particularly for the eye (ACIA, 2004) and for the skin of people standing up or sitting down. In the paper we have, however, used the accepted standard of erythema irradiance on a horizontal surface.

We calculate the vortex-averaged increases in clear-sky UV radiation with respect to climatology. This is done for spring 1996 and 1997, when the vortex was severely depleted and long-lasting. As a reference the same calculation was performed for spring 1982, when the vortex was long-lasting, but hardly any ozone depletion is expected. We have used a UV radiation code for the calculations as well as meteorological data. The UV radiation calculations have been validated against UV observations at a single high-latitude site, but all calculations have been performed for the whole vortex.

## 2 UV calculation

The clear sky UV fields of erythema irradiance are calculated using the widely employed radiative transfer model UVSPEC (Kylling, 1995; Mayer and Kylling, 2005) which is based on the discrete ordinate method DISORT (Stamnes, 1989) and has been thoroughly validated against measurements (see references in Mayer and Kylling, 2000). The calculations are performed with total ozone as the only temporally varying input parameter whereas climatological parameters are used for all other atmospheric input data as well as surface albedo.

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**Fig. 1.** Comparison of the calculated UV-index (solid, black line) to radiometer measurements at Tromsø (filled squares for clear-sky measurements, open squares for measurements weakly affected by clouds). The 1979–1981 mean UV-index is also shown (dashed). The period when Tromsø was inside the vortex are marked at the bottom of the plot. The dotted, red line is the ECMWF cloud cover.

We used the 360 nm albedo based on TOMS reflectivity data from 1979–1992 calculated with a moving time-window technique (MTW) (Tanskanen, 2004). The UV albedo is usually below 10%, but snow cover can increase the albedo up to 95%. During the March–April period studied here snow cover can vary a lot from year to year in certain regions, such as Scandinavia and adjacent parts of Russia. We therefore also tried to use the normal albedo calculated by the European Centre for Medium-Range Weather Forecasts (ECMWF), but only small differences were found in the vortex means presented below.

The total ozone data used are the National Institute of Water and Atmospheric Research (NIWA) assimilated total ozone data set, which uses Nimbus 7 and Earth Probe TOMS version 8 uncorrected and Meteor and Adeos TOMS and GOME normalized to the Dobson network (Bodeker et al., 2001, 2005). Compared to ground based Brewer measurements in Kangerlussuaq (67° N, 309° E) TOMS version 8 is slightly too low in April (~7 DU) leading to slightly too high calculated UV (~3%).

The UVSPEC programme has been used to make a lookup table with increments of 20 DU, 5°, and 50% in total ozone, solar zenith angle, and albedo, respectively. Linear interpolation in this table was found to be sufficiently accurate. The effect of aerosols are corrected for using the aerosol optical depth (AOD) at 300 nm found in the climatology from the Global Aerosol Data Set (GADS) (Köpke et al., 1997). We used the GADS summer data set, which a spatial resolution of 5° × 5° covering the globe. This is a coarse resolution in both space and time, however no other data are available with a global coverage. A simple correction for the effect of aerosols is applied to the UV irradiances by multiplication with  $\exp(-0.5 \cdot \text{AOD})$ .

We have used the UV-index as a unit of measure of UV levels relevant to the effects on human skin. It is defined as the effective irradiance obtained by integrating the spectral irradiance weighted by the CIE (1987) reference action spectrum up to 400 nm normalised to 1 at 297 nm and multiplying the time weighted average effective irradiance in  $\text{Wm}^{-2}$  by 40.

We have cut off the calculations at 75° solar zenith angle (SZA), to avoid biologically harmless levels of UV. For a total ozone amount of 300 DU and an albedo of 95% we get a UV-index of 0.78 at 75° SZA, which gives one minimum erythemal dose (1 MED=200  $\text{Jm}^{-2}$ ) during about 3 h.

### 3 Comparison to UV observations

In Fig. 1 the model results have been compared with measurements from the multichannel moderate bandwidth filter radiometer GUV-541 in Tromsø (69.7° N, 19.0° E) that is part of the Norwegian UV monitoring network (Johnsen et al., 2002). The calibrations are maintained with a travelling reference filter radiometer, calibrated by the Norwegian Radiation Protection Authority. The irradiance scale is traceable to the NOGIC2000 Nordic Intercomparison of UV and total ozone instruments that was arranged in Halmstad in June 2002. The comparison in Fig. 1 is done for local noon and only smooth bell-shaped daily profiles are used to avoid cloud affected days. On certain days (marked by open symbols) the profiles were not totally smooth. Both the MTW albedo climatology and the ECMWF albedo were between 36–44% for the whole period. The model results compare well with the observations. They are 6% higher on average, but this could be due both to modelling errors and observational biases. Small errors in the absolute UV levels are not too important in this study, where the emphasis is on relative UV increases. The cloud cover shown in Fig. 1 is the ECMWF cloud cover at the analysis time closest to local noon. Only a minor fraction of the clear-sky observations are made when the ECMWF cloud cover is small indicating that this parameter is not too useful at individual sites.

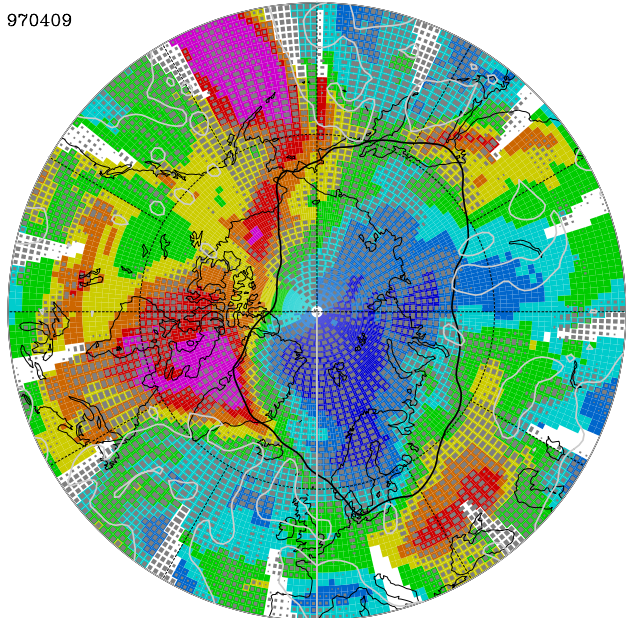
### 4 Results

In spring 1996 and 1997 the vortex ozone depletion was substantial (e.g. Rex et al., 2004; Knudsen et al., 1998; Goutail et al., 2004; Harris et al., 2002; Tilmes et al., 2004) with the depletion maximising at around 100 DU. In both years the vortex lasted well into April. The same is true for spring 1995, but no TOMS or GOME ozone data are available for this period. In spring 2000 and 2005 large ozone depletions also occurred, but a vortex break-up in mid-March prevented high UV levels beneath the vortex.

As an example of the effect of the depletion on the ozone column Figs. 2a and b show the column ozone for two selected days in April 1996 and 1997. The approximate



TOMS total ozone (DU)  
 ■ -280 ■ -310 ■ -340 ■ -370 ■ -400 ■ -430 ■ -460 ■ 460–  
 970409



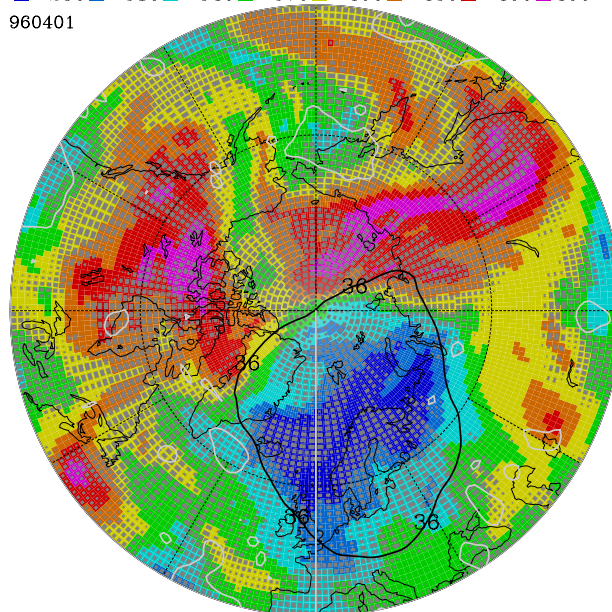
**Fig. 2. (a)** NIWA assimilated total ozone north of 40° N on 9 April 1997. The thick black contour is 36 PVU of the 475 KPV, whereas the white contour is 6 PVU of the 350 KPV. Grey dots mark cloud cover (see text).

position of the polar vortex is indicated by thick black contours of 36 PVU ( $10^{-6} \text{ Km}^2 \text{ s}^{-1} \text{ kg}^{-1}$ ) of the 475 KPV (potential vorticity). It is evident that very low ozone values occur inside the vortex. The ECMWF analysed total cloud cover is indicated by the grey dots. The grey dots occupy 70% of each pixel in both meridional and zonal direction, i.e. 49% of the area of the pixel for totally overcast conditions, whereas for smaller cloud fractions the dots are reduced proportionally. No dots are drawn for a cloud cover below 2 octas (25%).

One might think that the frequent ozone mini-holes are the dominating factor in high UV episodes in the Arctic. According to ACIA (2004) this is not case: the high UV episodes are dominated by the vortex low ozone episodes, at least in years with severe depletion. On one hand an ozone mini-hole is connected to a high-pressure system and usually cloud-free conditions, whereas it usually is more overcast beneath a vortex. On the other hand a depleted vortex is much larger than and occurs much more frequently in the Arctic than ozone mini-holes. Please note that the ozone mini-hole climatology by James (1998) includes episodes of low ozone inside the vortex. Ozone mini-holes are of course also affected by the general ozone depletion and have particularly low ozone columns in recent years.

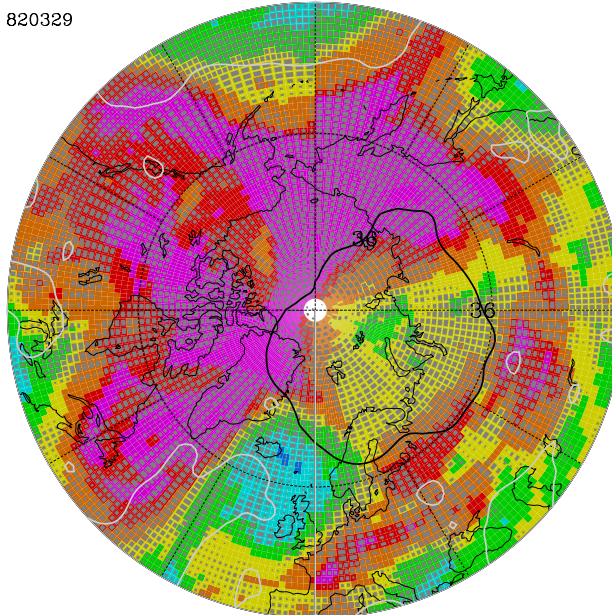
Ozone mini-holes are caused primarily by transport of low ozone from lower latitudes (Koch et al., 2005). Such low-latitude air will retain its low PV for a long time and should be detectable in ECMWF analysis for several days. In Fig. 2

TOMS total ozone (DU)  
 ■ -280 ■ -310 ■ -340 ■ -370 ■ -400 ■ -430 ■ -460 ■ 460–  
 960401



**Fig. 2. (b)** As Fig. 2a, but for 1 April 1996.

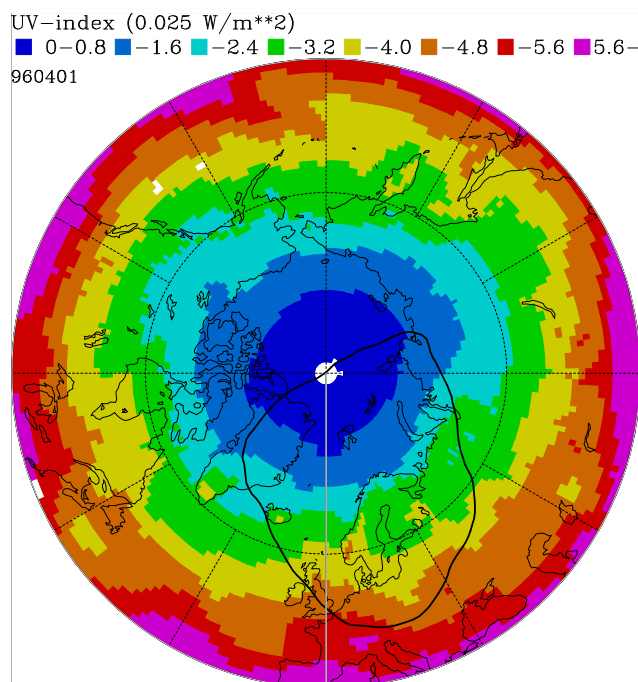
TOMS total ozone (DU)  
 ■ -280 ■ -310 ■ -340 ■ -370 ■ -400 ■ -430 ■ -460 ■ 460–  
 820329



**Fig. 2. (c)** As Fig. 2a, but for 29 March 1982.

the 6 PVU contour of the 350 K isentropic PV is therefore plotted as well, and it does seem to track the ozone mini-holes reasonably well.

To quantify the non-anthropogenic dynamical influences on the vortex ozone columns we have looked at the



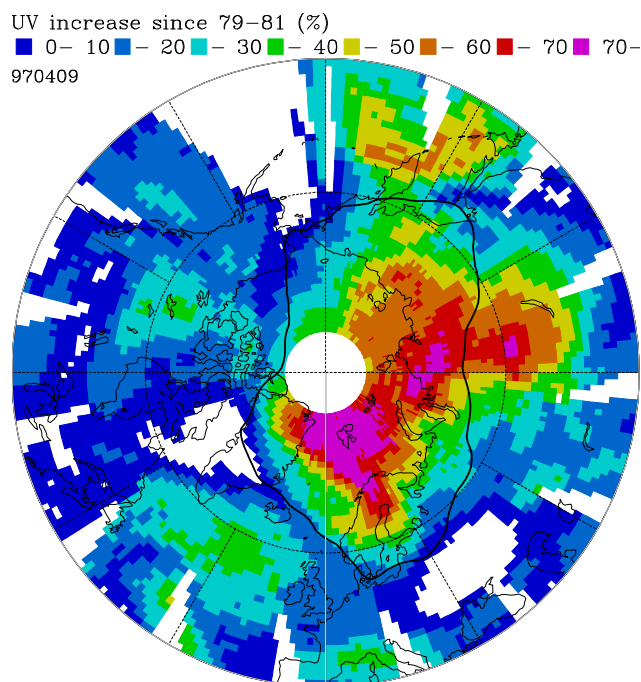
**Fig. 3.** Clear sky UV-index on 1 April 1996. Black contour marks vortex edge.

1981–1982 winter when the vortex lasted into April. Polar stratospheric clouds and chlorine were very sparse so only little chemical ozone depletion is expected. The March averaged column ozone at Thule (76.5° N, 68.8° W) for days when the station was inside the vortex, was at its lowest during the period 1979–1988 in 1982 (Andersen, 1999), indicating that 1982 will give us the approximate maximum dynamical influence on the vortex UV levels. Figure 2c shows the low ozone columns inside the vortex on 29 March 1982.

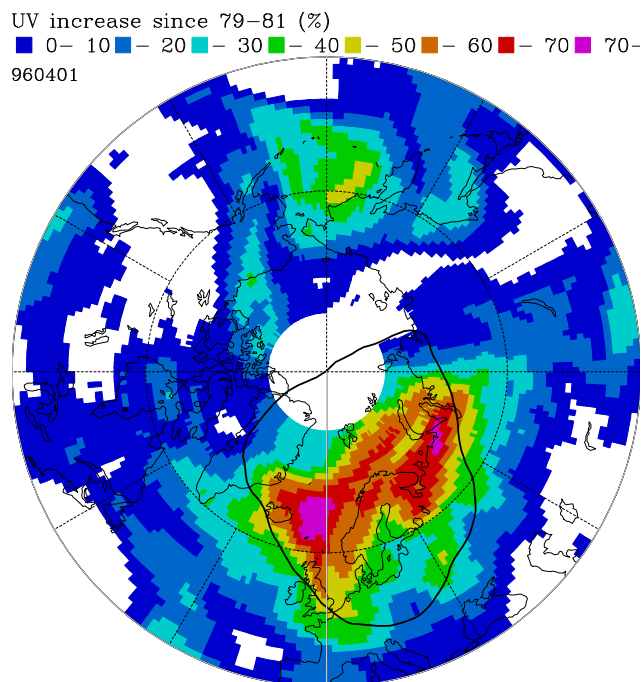
Figure 3 shows the clear sky UV-index (the unit is  $0.025 \text{ W m}^{-2}$ ) on 1 April 1996. Please note that altitude has not been taken into account in the UV calculations. In the remainder of the paper we focus on relative increases of UV, which more or less are independent of the altitude.

Clear sky UV is calculated for each day in March–April 1979–1981 as a reference. This field is smoothed by averaging over 11 days for all 3 years. Figure 4 shows the clear sky UV increase relative to the 1979–1981 period for the three days shown in Fig. 2. This figure shows substantial increases in UV under the depleted vortices in 1996 and 1997. These UV increases are of interest since UV-protection (e.g. sunscreen) might be necessary in case of clear sky. In 1982 there is a small increase in UV relative to the climatology.

Figure 5 shows the vortex averaged clear sky UV increase, clear sky UV-index, cloud cover, and equivalent latitude of the edge of the vortex for each day in the 3 years studied. The curves stop when the vortex breaks up. Panel (d) shows that the vortex in 1982 and 1996 diminished its size substan-



**Fig. 4. (a)** Clear sky UV increase relative to 1979–1981 (%) for 9 April 1997. Thick black contour marks the vortex edge.



**Fig. 4. (b)** As Fig. 4a, but for 1 April 1996.

tially prior to actual break-up. It is necessary to be cautious about results obtained during this period because the vortex can be flushed with outside air and split up. Periods of vortex splitting are indicated by dashed lines in this panel. In panel



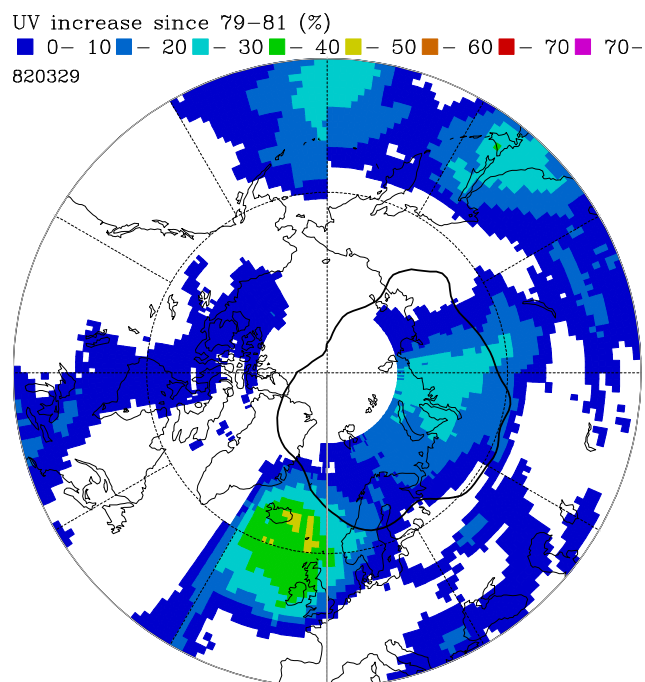


Fig. 4. (c) As Fig. 4a, but for 29 March 1982.

a circles mark the days used in Figs. 2–4. The days with maximum UV increase in 1996 occur during ozone mini-hole episodes affecting the vortex. The average increase from day 80–100 was 6.7, 35.9, and 33.0% in 1982, 1996, and 1997, respectively. The UV increase in 1982 is our best estimate of the maximum non-anthropogenic dynamical contribution to the increases in 1996 and 1997. In 1996 and 1997 there may be a larger dynamical contribution than in 1982, but this could be due to anthropogenic influence. The UV-indices in panel (b) are influenced by how far off the pole the vortex is displaced. Particularly during vortex split-up parts of the vortex can move quite far south. In 1996 the vortex moved far south and thus affected midlatitude sites (Seckmeyer et al., 1997). A rather high cloud cover each year is revealed in Fig. 5, panel (c).

Figure 6 shows the maximum clear sky UV increase experienced underneath the vortex on a single day from 15 March to break-up. As the vortex moves around at any given location only the days when the vortex was above are considered. Only days when the cloud cover was below 2 octas are used. Individual pixels should be used with caution due to the above mentioned problems with the cloud cover. Both in spring 1996 and 1997 large parts of the Arctic experienced substantially elevated levels of UV radiation. For the maximum increase of 97% found in 1996, the time to get sunburnt almost halved, showing the importance of making UV-forecasts.

Figure 7 shows the maximum UV increases found outside the vortex. These are on average much smaller than those

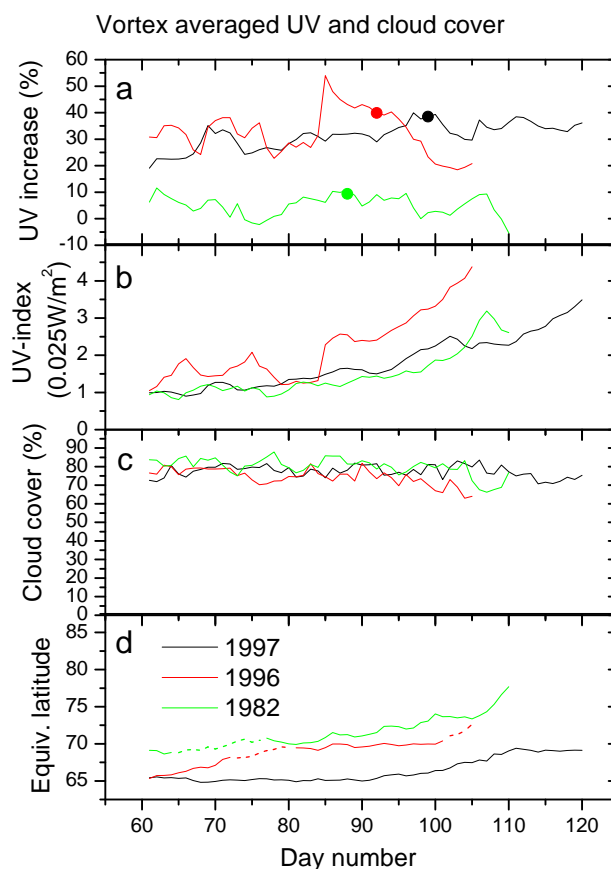
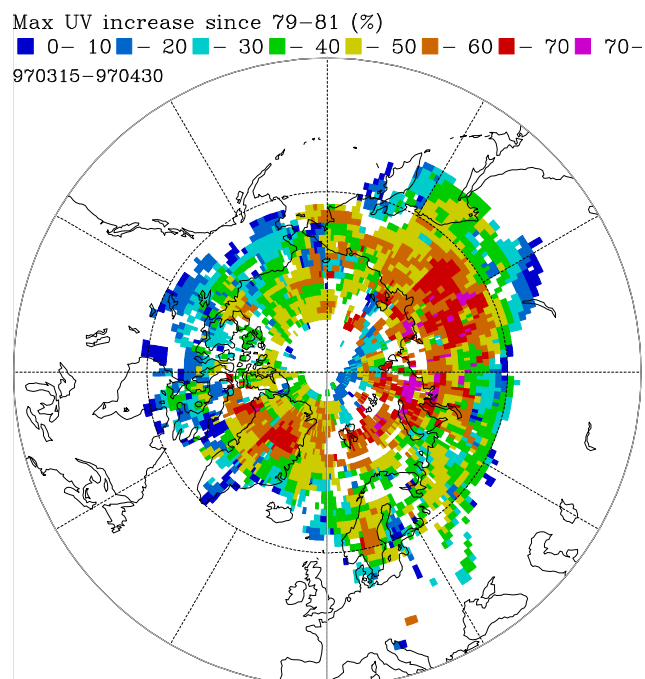


Fig. 5. Vortex averaged clear sky UV increase (a), clear sky UV-index (b), cloud cover (c), and equivalent latitude of the edge of the vortex (d). Periods of vortex splitting is indicated by dashed lines in panel (d). In panel (a) circles mark the days used in Figs. 1–3.

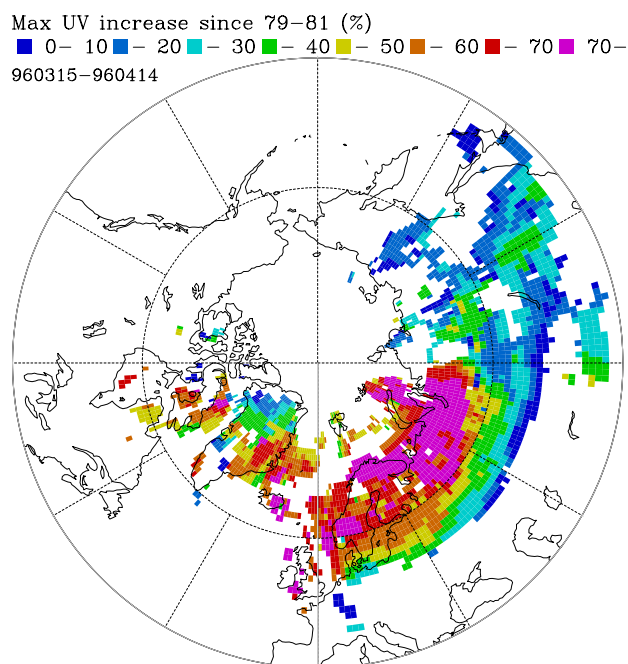
inside the vortex. Most of the large UV increases are in fact connected to the vortex since they occur for 475 K PV values between 30–36 PVU. This region should to some degree be isolated from the surf zone (zone of approximately constant PV between the vortex and the tropics) due to substantial gradients in PV. Inspection of 475 K PV and temperature maps reveals that in the winter 1995/96 temperatures low enough for polar stratospheric clouds to exist were unusually often found outside the polar vortex. Chemical ozone depletion could thus help explain the low ozone values found in this region, but the fact that the actual edge of the vortex on some days is at PV values below 36 PVU may also contribute.

## 5 Conclusions

Our calculations show that high UV levels do occur below severely depleted Arctic vortices and this situation is likely to continue for many years to come. These depletions can affect midlatitudes, when the vortex moves southward, as measured in 1996 (Seckmeyer et al., 1997). The vortex ozone

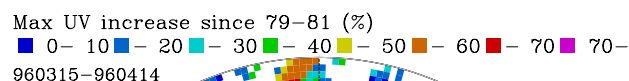


**Fig. 6. (a)** Maximum UV increase inside the vortex since 1979–1981 (%) on clear sky days from 15 March to vortex break-up in 1997.



**Fig. 6. (b)** As Fig. 6a, but for 1996.

depletions will eventually spread out to midlatitudes after vortex break-up and cause ozone reductions (Knudsen and Andersen, 2001), which probably lead to increased UV.



**Fig. 7.** Maximum UV increase outside the vortex since 1979–1981 (%) on clear sky days from 15 March to vortex break-up in 1996.

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